II

FINAL REPORT

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PASSIVE IR SO_2 SENSOR

Prepared for

PUBLIC HEALTH SERVICE ,BSS-EH

Washington DC

PH 86-66-155

DALMO VICTOR

BELMONT, CALIFORNIA

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SO_2 SENSOR

Prepared for

Public Health Service, BSS-EH

Washington, D. C.

by

Dalmo Victor Company

Division of Textron, Inc.

1515 Industrial Way

Belmont, California

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Prepared by: James M. Lepper Jr.
James M. Lepper Jr.
Project Engineer

Approved by: John Landre
John K. Landre
Technical Manager
Environmental Pollution
Projects

Approved by: W. A. Porter
W. A. Porter
Executive Director
Product Planning & Research

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ABSTRACT

Under contract to the Public Health Service, a remote operating Passive Infrared SO_2 Sensor was developed. A system of quantitative measurement for field operation was created with simplicity of operation and minimun of interference as objectives. The complexities of the radiative process limit accuracies relative to laboratory measurements, but were overcome to the degree that meaningful and practical measurements are made in the field without further calculation. While there are limits to the environmental compensation and rejection, no other existing means approaches these limits to the degree of this Passive Infrared SO_2 Sensor.

The instrument is a four color radiometer with an orthogonalized ratio computer which computes the ratio of SO_2 radiation at 8.7 microns to the CO_2 radiation at 9.4 microns. The spectral overlap for each of four signals is stored in the sensor's computer. The mixed signals (four component vectors) from the four signal channels are separated (orthogonalized) by summing appropriate amounts of each channel (vector coordinate transformation). Two of the separated signals (perpendicular vectors) go to a phase detector which generates a function of the two components as the arctangent (the vector sum angle) of the component ratio. The ratio function is separated from the arctangent function by the non-linear scale of the panel meter.

SUMMARY

Dalmo Victor Company has designed and built a remote SO_2 Sensor under contract with the Public Health Service, BSS-EH. Part I of this final report presents the general problem of remote sensing and elaborates on the specific problem of quantitative analysis in situ. Dalmo Victor's solution, the passive infrared multicomponent analyzer, is described in terms of theory, implementation, and function.

Part II discusses the specifics of the instrument: mathematical development, detail block diagram, and manufacturing steps. Such details as are appropriate to a prototype development are supplied. These in turn form the ground work necessary for use of Part III.

Part III is the operational section, giving explicit instructions for lab and field setup, operation and modification. Environmental parameters are given with charted limits.

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PART I

PROJECT DEVELOPMENT AND OBJECTIVES

A. INTRODUCTION

This report summarizes the development and function of the Dalmo Victor passive infrared SO_2 Sensor per Contract PH = 86-66-155. The work consisted of design and construction of a four channel, passive infrared radiometer which measures the amount of SO_2 8.7 micron radiation in the plume of a fossil-fuel thermal plant, particularly coal fired electric power plants. Sub-systems with which Dalmo Victor had previous successful experience were combined into a new system to demonstrate feasibility of a concept as yet unequaled as a remote sensing system. While certain of the target characteristics prevent blanket application of the system, the radiometer functions as predicted, and opens a new field of remote, quantitative analysis.

When a target is satisfactorily defined, as in the case of the coal burning plant, the qualitative information is available to the worker, and only the quantitative analysis remains. The Dalmo Victor SO_2 sensor performs the quantitative measurement by referring the signal strength of the SO_2 to a known signal strength, CO_2, and by subtracting proper portions of the interfering and background signals.

B. PURPOSE

The purpose of this instrument is remote sensing of SO_2 as a field measure of atmospheric pollution potential by various fossil-fuel thermal plants. The instrument is portable and needs to be brought only within a range of 100 to 1,000 meters. With cursory examination of the field of view and background, the instrument is set up, balanced against its background and operated for as long as is necessary to get an average of that particular target. The ratio of SO_2 to CO_2 in the plume is read directly off the instrument panel with no further calculation. A photograph of the SO_2 Sensor Unit is presented in Figure 1.

C. THE PROBLEM

Isolation of the SO_2 radiation received by the instrument involves multiple capabilities within the instrument. The signal as radiated from the target plume is partially obstructed by the atmosphere and superimposed on the background radiation and radiation due to spectrally overlapping components of the plume. Further obscuration will result depending on the amount of flyash in the plume.

Radiation from the plume varies as a function of the emissivity of the constituents and the temperature of the plume. The variations due to temperature are described by the Planck blackbody radiation curves shown in Figure 2, where the radiation at 8 and 10 micron wavelengths is shown versus the temperature of a radiating source. The energy density with respect to wavelength is a product of the emissivity and the blackbody radiation function. In the special case where the plume is optically very thick the emissivity of all wavelengths approaches one, and the radiation is described solely by the Planck radiation function. In the latter case, no information may be obtained from the plume beyond a measure of its temperature.

Plume constituents of significance in a radiative SO_2 measure are CO_2, H_2O and fly ash. These spectrally overlapping constituents and the background were examined and described in detail in the final report, "Study of Infrared Techniques for Monitoring Stack Gasses." Final Report for Study of Infrared Techniques for Monitoring Stack Gasses R-3159-3954, Contract PH 86-65-61 Dalmo Victor Co., Belmont, California 1965. Both the ash and the H_2O spectra are very broad and overlap SO_2 and CO_2. The spectra of the gasses are of similar strength in the region 8 to 10 microns while the spectra of the ash can vary from negligible to complete obscuration, depending on the quality of the thermal-system ash recovery.

Since the plume must have an emissivity (equal to the absorbtivity) much less than one to discern its contents, the background will show through it. The background may consist of the sky, clouds, hills or structures. In the case of the sky the spectral distribution for background radiation is determined by the combined effect of the temperature lapse with altitude and the spectral transmission of the varying atmospheric constituents. A distinctive feature of the sky background (9.6 microns) is caused by relatively hot ozone while the effective radiative temperature of the sky runs from about 220° to 280° K. This is due to ozone in and below the inversion layer and ozone in the upper stratosphere generally between 15 and 45 kilometers.

In the case of clouds, the background is effectively the cloud base temperature. The spectrum of the cloud base is generally uniform as opposed to the distinct sky spectrum. Further, the clouds are frequently moving in and out of the field of view. Those clouds which are at high altitude change slowly compared to the rate of measurement and can be dealt with, as can clouds which present a continuous overcast.

Ambient backgrounds can cause significant error in cool plumes. If the plume of stack gasses has mixed with air, or is otherwise cooled to the background temperature of a sunlit background at 120° F for example, there will be no distinction of radiation from the gas and the background. The gas will emit just the amount of radiation it intercepts from the background; i.e., it acts as a relay with a gain of 1 and becomes invisible. For a ratio sensor the effect is only one of signal loss if the background emissivity is uniform. An example has been worked out for a common case where the background is

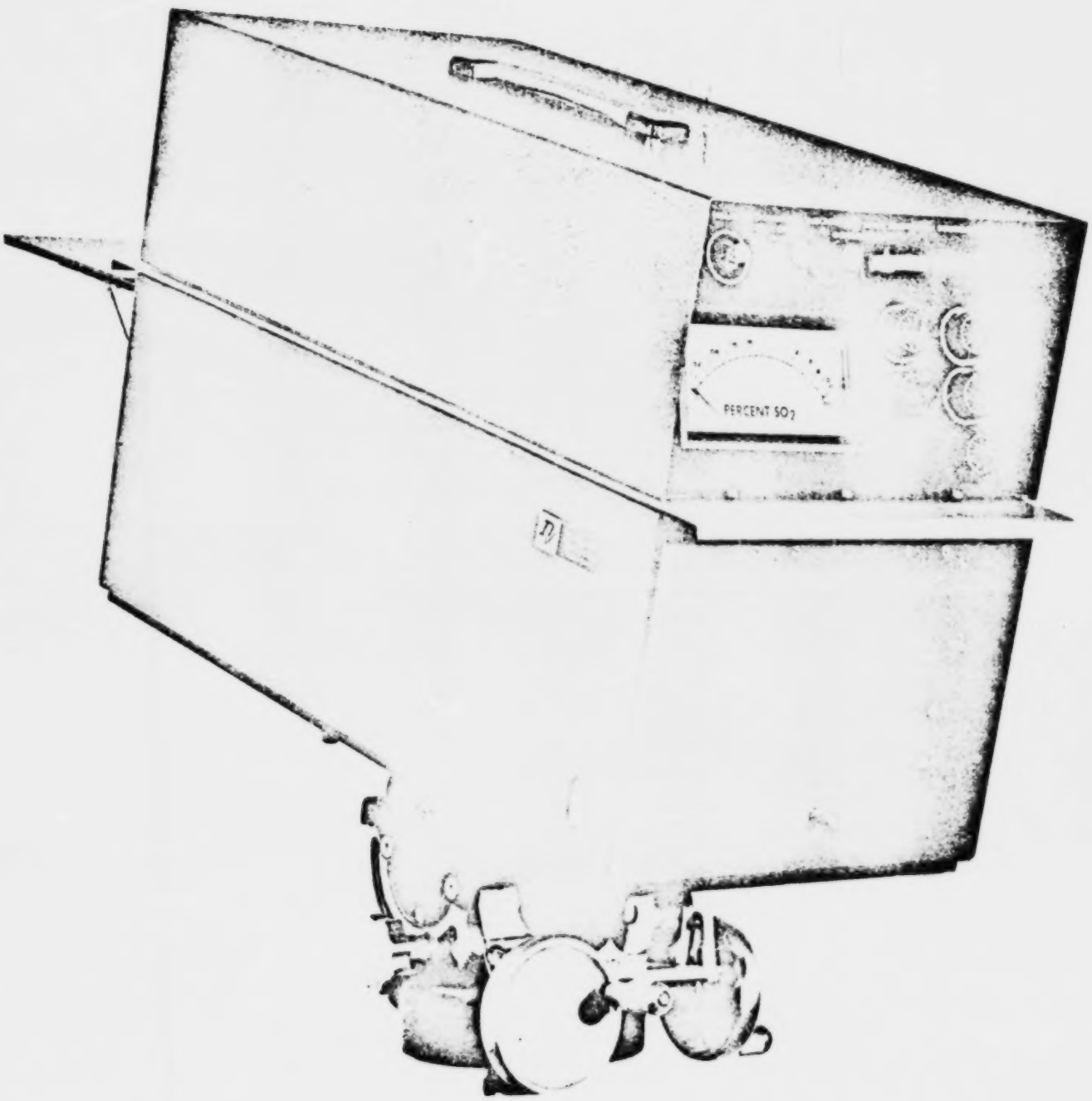

Figure 1a. SO_2 Sensor Unit

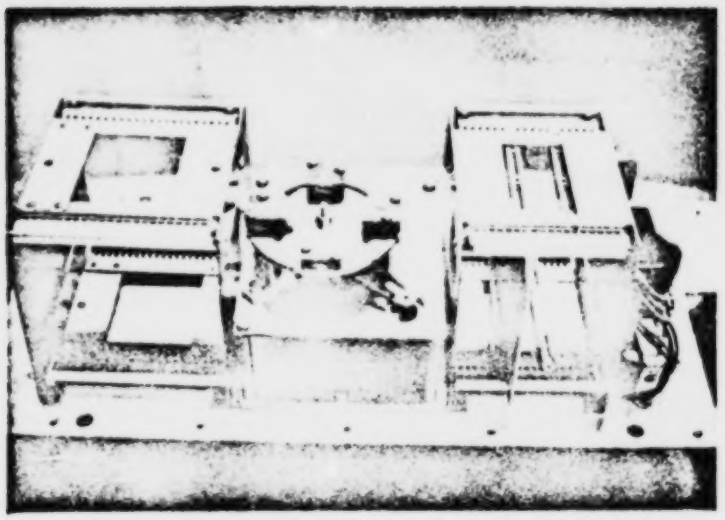

Figure 1b. Electronics Chassis

Circuit card holders are on either side of the filter wheel-chopper assembly.

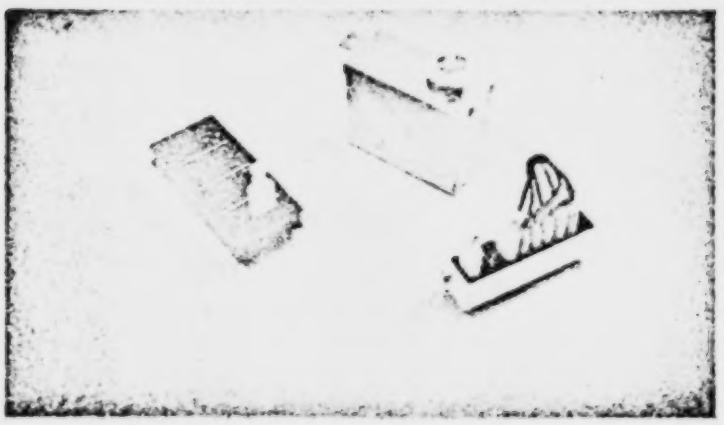

Figure 1c. Bolometer Mount and Patch Panel Components

The pre-amp package is mounted in a shielded housing with the bolometer directly coupled.

The patch panel components select the signal processing format after decommutation.

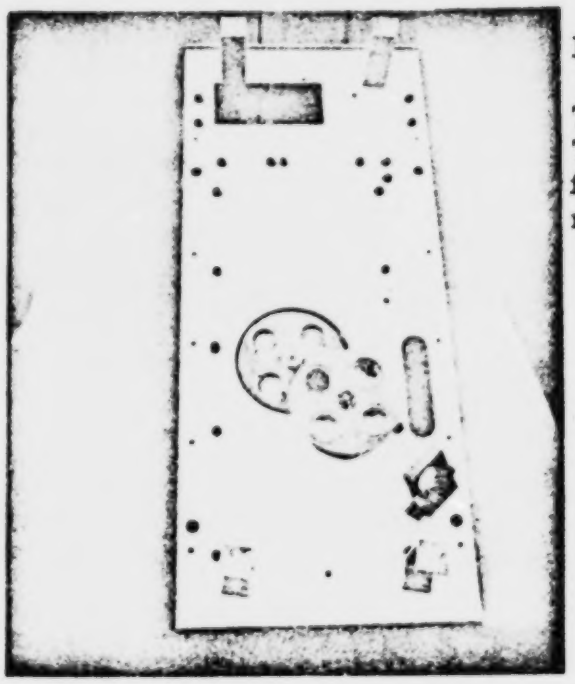

Figure 1d. Electronics Chassis Underside

The four primary filters go in the recessed disc. The outer disc holds the blocking filter or test filters. Note the holder for the telescope transfer mirror.

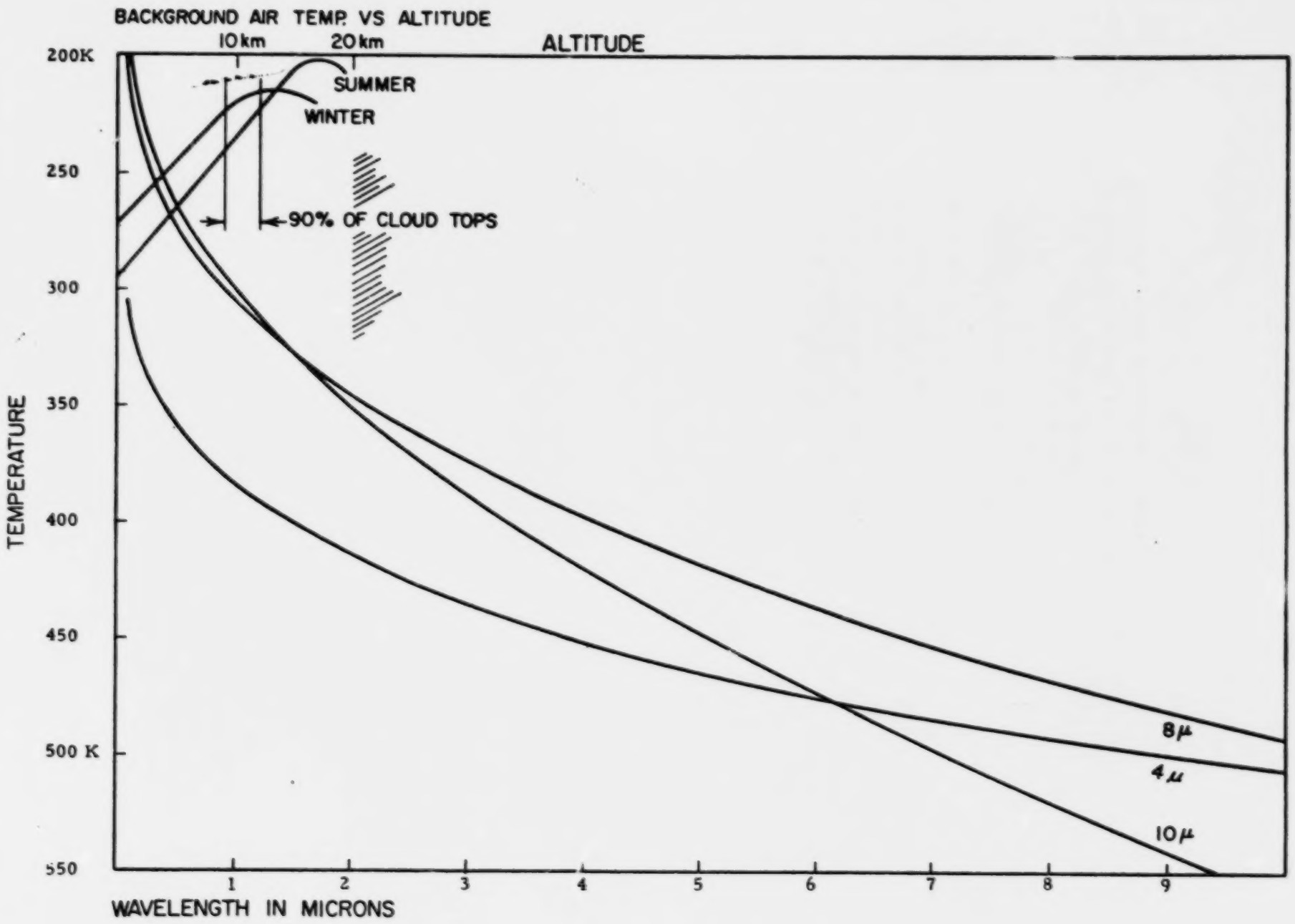

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Figure 2. Planck Black Body Radiation Curves

not spectrally uniform (clear sky with ozone) but significantly cooler than the target plume. An error of about 7.7% in SO_2/CO_2 ratio occurs for the following:

Background emissivity, SO_2 band	0.3
Background emissivity, CO_2 band	0.9
Background temperature	260° K
Target temperature	400° K

D. THE SOLUTION

The strongest effect in the radiative transfer of the SO_2 signal is due to radiation strength as a function of plume temperature. This effect is cancelled over a fairly wide range of operating temperatures by taking the ratio of the SO_2 signal to the CO_2 signal. As was shown in Figure 2, the Planck radiation potential of the SO_2 band differs only a few percent from the CO_2 band potential over the range of temperatures, say 400° K to 500° K. Thus the CO_2 becomes not only the reference for concentration but the reference for temperature as well. The technique used to compute the SO_2 to CO_2 ratio has been previously demonstrated in Dalmo Victor Infrared Systems and was directly adapted to this instrument. The ratio is computed by means of an arctangent alogarithm and presents a non-linear readout in the instrument panel. For the purposes of this instrumentation the non-linear readout is actually an advantage since it compresses the ends of the scale. Ratios zero through infinity may be represented while retaining a reasonable display scale around the center value of 0.1% (of total plume or 1:100 SO_2/CO_2).

Separation of the overlapping spectral constituents is done by means of a matrix inversion technique. Since there are four unknowns involved, it is necessary to make four measurements to solve for any one of the constituents. Further, the same four measurements, with proper manipulation, can isolate any of the other three constituents. The mathematical description of the matrix is presented in Part II. In essence, the matrix supplies the transformation necessary to take four mixed signals (non-orthogonal vectors) and separate them into their pure components (orthogonal vectors). This transformation by matrix is a quite general procedure and is suitable for any of several measures, such as computing the ratio of fly ash signal to CO_2 or computing SO_2 to the sum of CO_2 and H_2O.

Sixteen laboratory measurements of gas samples are tabulated in a 4 x 4 matrix. The inverse of the matrix, taken by computer, is entered in the sensor as calculation coefficients. With further gathering of data and entering of the appropriate inverse matrix into the machine, other gasses may be sensed and quantitatively measured. Note that the matrix technique uses a priori information, i.e., the qualitative measure of the target is made first, but only once, while the quantitative measure is made with each field trial.

The a priori information is gained through a set of four laboratory experiments, each involving four measurements. For example, pure H_2O is placed in the chamber at a temperature in the general range anticipated for field use. The signal strength in each of the four spectral filter channels is then measured. The values are normalized to the largest of the four signals

for electrical processing convenience. Thus a matrix of 16 data is produced where four of the data are normalized to unity. The ratio of the SO_2/CO_2 signal, to the SO_2/CO_2 concentration in the test tank, is made with a 1 to 100 gas ratio in the test tank and entered as the scale factor. This scale factor may be also used to compensate for fuels with different amounts of CO_2 - thus, there is a percent CO_2 knob which accomplishes these scalings.

Further information is permanently incorporated in the sensor in the form of the filter characteristics for each of the four channels. The filters for this system are interference filters which may be specified by band width and band center. Incorporation of the spectral characteristics of each of the four plume constituents in a computer program allowed a computer to select an optimum set of bandpass filters. A signal-to-noise maximization was chosen for the filter selection.

It should be noted that it is not desirable to cross-correlate the filter spectrum with the incoming spectrum, since corss correlation implies a qualitative measure rather than a quantitative measure.

A measure of the difference in filter selection approach may be had by comparing the figure of merit compared for "ideal" square-band filters with that figure computed for realizable filters.

The realizable filters have a transmission curve intermediate between the ideal filter and one modeled after the target gas. The figure of merit for the ideal filters was 12442 while that of the realizable filters was 9762. The overlap of spectra due to sloping band edges is a definite disadvantage.

While information theory clearly shows that cross-correlation will give the maximum signal-to-interference ratio when the interference is unknown, it does not guarantee that the interference will be zero. If the interferer is known and quantified, it may be subtracted exactly (with consideration for signal-to-noise, where the noise is electronic).

E. IMPLEMENTATION

With reference to the general block diagram, Figure 3, the following is a description of the components and subsystems required to implement the matrix separation and ratio presentation of the SO_2/CO_2 signal.

The signal is received by the bolometer detector as a pulse amplitude modulated sequence of four filtered, radiative signals. The four filters, whose design was selected by the computer program above, are mounted on a

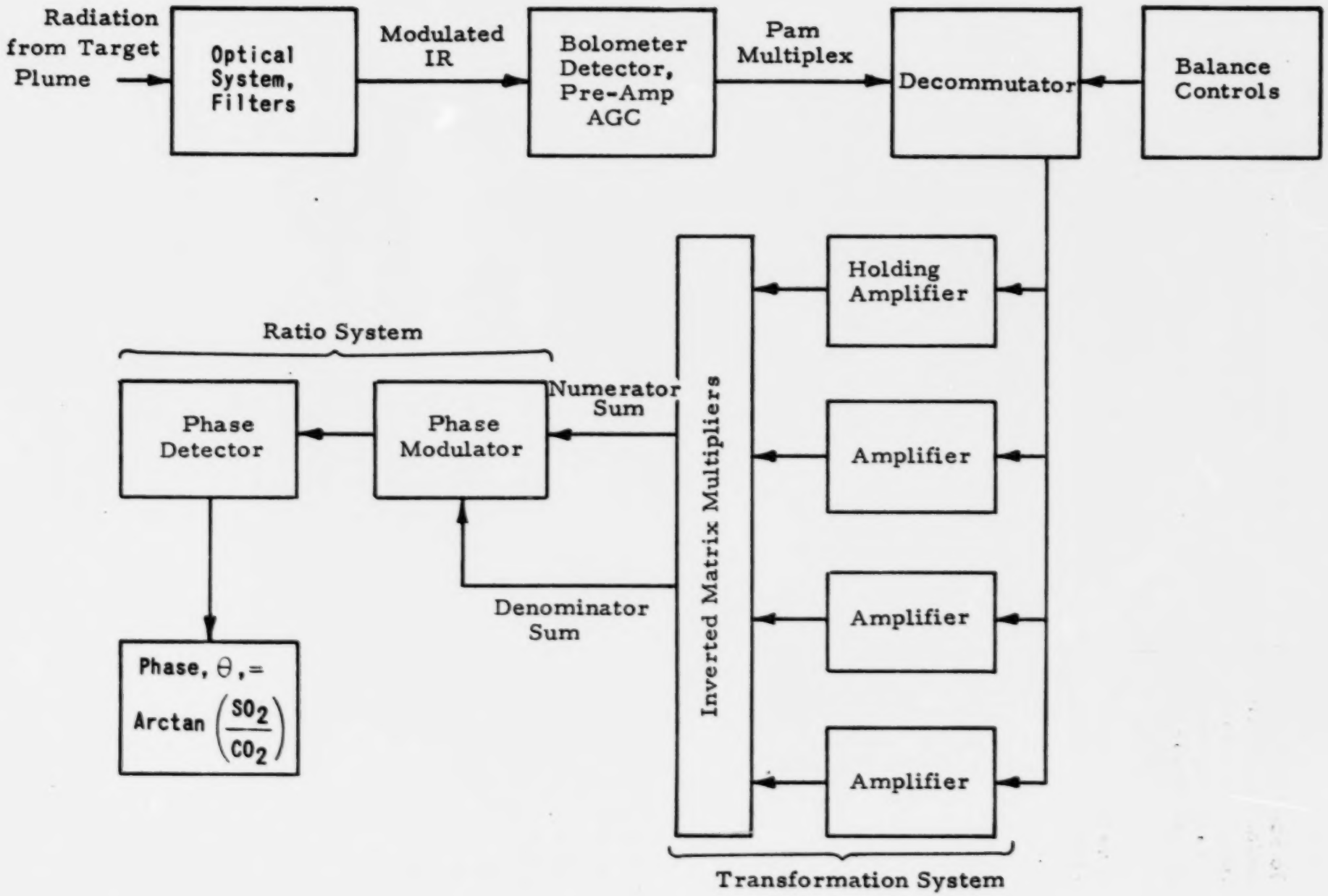

Figure 3. SO_2 Sensor Block Diagram

wheel turning at approximately 25 revolutions per second. The sequence of filtered signals is interrupted by the spokes of the filter wheel. The spokes reflect within the optical chassis of the sensor and act as a reference signal proportional to the temperature of the sensor chassis. The thermal mass of the sensor system causes this reference to remain sufficiently stable during system operation.

The sequence of the signals from the filters is decommutated after the bolometer amplifier. Each decommutated signal has its own holding amplifier. The output of the four amplifiers is thus continuously available to the rest of the system, and is no longer in a serial multiplex format. Balance signals are injected at the time of decommutation and are manually controlled with reference to an instrument signal strength indicator. An automatic gain control is incorporated in the bolometer amplifier to keep the general range of signals within the dynamic capabilities of the computer. The signals of each amplifier are connected to the matrix transformation components by way of a patch board. The patch board was included to give flexibility in determining which components of the signal are to be calculated. It was particularly useful during the development phase where only the SO_2 and the CO_2 were calculated and later, where the SO_2, CO_2 and H_2O were calculated.

The transformation involves each of the four input channels for each component solved. They are patched-in with connections for the numerator (SO_2), and with connections for the denominator (CO_2) of the system calculation. The proportions patched-in are controlled by a set of potentiometers. The potentiometer values are set by monitoring their throughput from an internal reference voltage. The settings are taken directly from the inverted data matrix.

The numerator and denominator components are fed to a ratio taking device which consists of a phase-modulation, and demodulation, computational alogarithm. The solution appears as an electrical phase angle and results in an arctangent function output from the system phase detector. The scale then reads zero ratio for zero degrees and infinite ratio for 90° electrical phase.

F. MECHANICAL CHARACTERISTICS

1. Objectives

The mechanical design of the SO_2 sensor represents compromises between a professional, commercial appearance and a research device which may be readily modified. Accessibility and flexibility in the design are of special concern with a feasibility instrument. Further attention was given to the problem of operator convenience in the field since it was expected that a large amount of data gathering time would be accumulated with this system.

2. Layout

The system is divided functionally into two sub-chassis: the optical chassis and the electronic chassis. This division isolated development problems and presents a simple package configuration. A side view diagram is shown in Figure 4.

The optical chassis was designed with rigidity as the foremost criterion while accessibility and developmental flexibility were retained. All of the optical components are mounted on a thick aluminum base plate; the primary mirror is in sliding ways having two inch focus travel. The focus travel is necessary for viewing laboratory targets at ranges down to six feet. Because of the large system aperture and the small field of view at short ranges, a sighting system without parallax is necessary for development tests. Thus, the sighting telescope uses a pair of transfer mirrors which give a coaxial boresight.

The electronic chassis has a cover which is readily removed by use of four captive screws. All of the electronic circuit boards are immediately accessible on the left side of the instrument while the wiring loom is completely accessible on the right side of the instrument. The filter wheel and drive assembly are located between the two circuit-card racks. For drive frequency stability a hysteresis-synchronous motor is used. An indirect drive is incorporated to make certain that the chopping frequency is not harmonic with the 60 Hertz power line. The indirect drive serves two other purposes: low heat transfer through the drive shaft to the filter wheel assembly occurs; and quiet, damped coupling is obtained. A commutator assembly is mounted on the same shaft as the filter assembly providing the necessary signal processing synchronism. The commutator assembly consists of a chopping sector-wheel with four lamp-photodiode assemblies.

The control panel is sloped 20° off normal to present a convenient viewing angle for typical field elevations. It further provides protection of the instrument meters and controls. The signal strength meter is mounted immediately adjacent the sighting scope. The sighting scope is a pistol type providing at least 18 inches eye-relief; thus, simultaneously a view of the target through the scope is available while monitoring signal strength indication with the peripheral vision or, at most, a quick glance.

3. Test Tank

To determine the system throughput for each spectral source a laboratory setup is necessary to simulate the cross section of a typical target, as shown in Figure 5. A one meter heated test cell with infrared windows was mounted on a heavy-duty cart with the ancillary equipment such as a vacuum

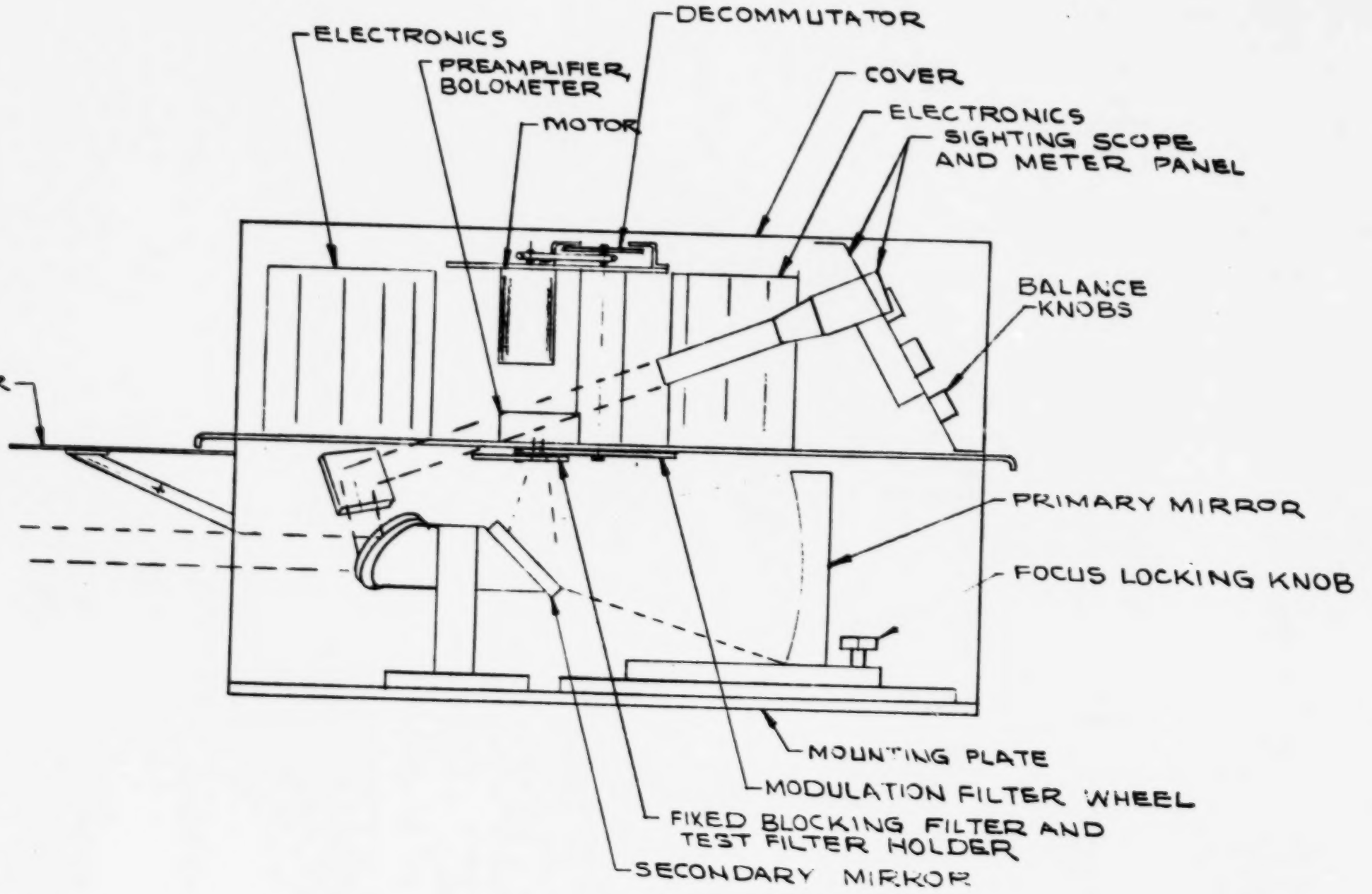

Figure 4. SO_2 SENSOR INTERNAL ARRANGEMENT

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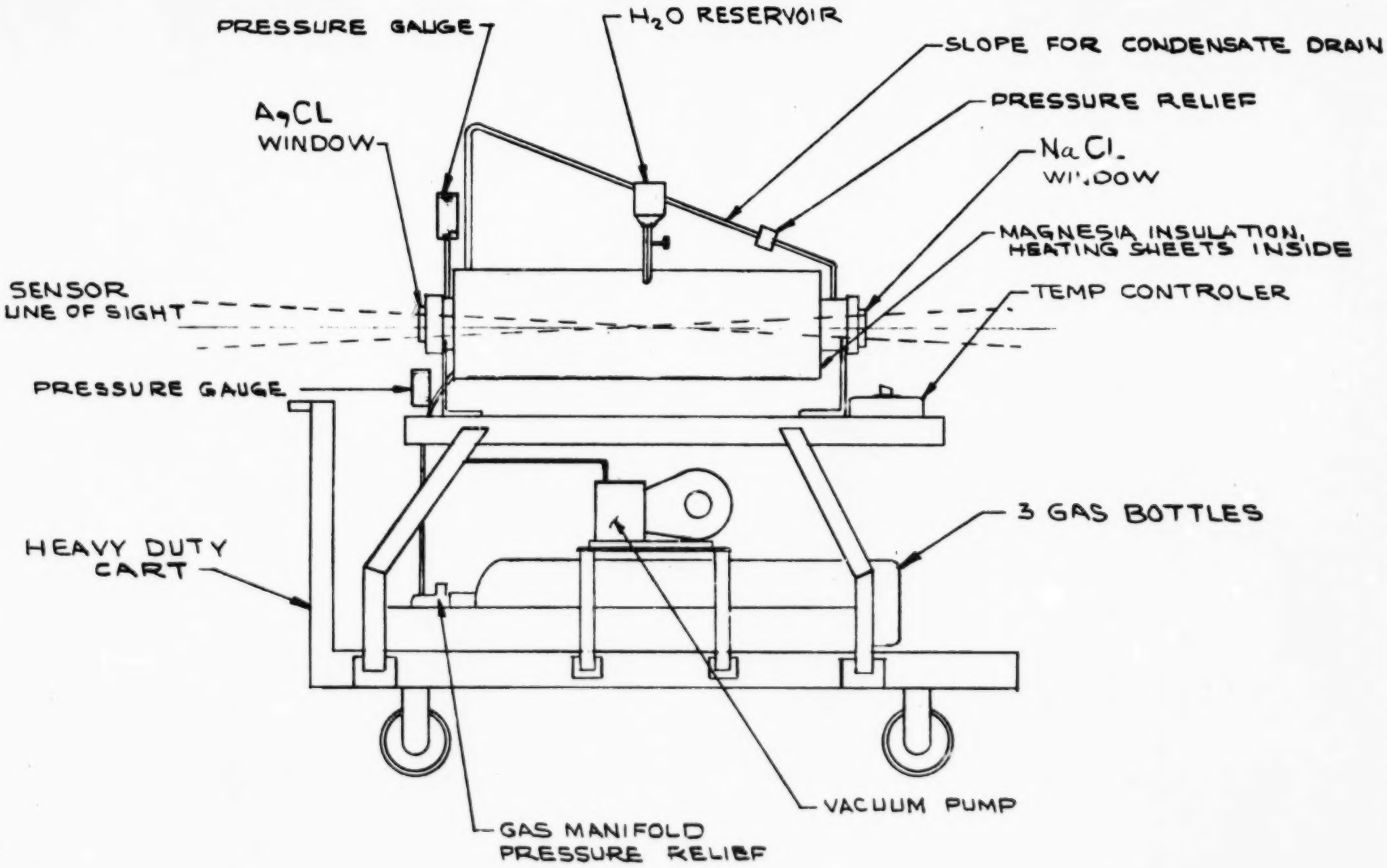


Figure 5. Test Tank

pump, plumbing, etc. The tank has a 2-1/2 inch clear aperture at each end. The optical system of the sensor has a six inch aperture. The relatively inexpensive 2-1/2 inch windows were made sufficient by focusing the sensor in the center of the tank; thus, the beam from the sensor necks down in a cone to less than 2-1/2 inches at the entrance, is on the order of 0.1 inches (3 mm) in diameter at the tank center, and expanded back to less than 2-1/2 inches at the exit.

The windows were sodium chloride optical-quality crystals in O-ring mounts. The O-rings provided inadequate seal and a semi-permanent seal of silastic was applied after each window change.

Considerable difficulty was encountered with the sodium chloride windows due to heat transients. Cooling the windows from 400°F to ambient in less than half an hour usually resulted in fracture. Improvement was obtained by use of silver chloride windows; however, the higher index of refraction causes more signal loss and stray radiation from the hot metal. The refraction errors are due to the softness of the Ag Cl; it became scratched and distorted due to vacuum-pressure cycling.

For quantitative measure of gases in the sample chamber a pair of pressure gauges were read during chamber filling, while three thermocouples supplied temperature information.

Additional fixtures for controlled water induction and ash sample mounting completed the test system.

G. REMAINING PROBLEMS

The primary problem of this system in the field is associated with lack of flyash control in the target plumes. While it may be argued that it is appropriate that the plant operator solve his particular emission problem before we worry about his SO_2 emission problem, the practical situation involves a requirement of SO_2 measurement before or during the steps necessary to clean up the ash. The effect of the ash, as mentioned above, is to cause the plume emissivity to approach one, whereby all information except that pertaining to temperature is obscured. Even given sufficient signal-to-noise, the system cannot separate large quantities of ash because of the non-linearity of emissivity vs. quantity as emissivity grows above the range 0.1 - 0.3. The matrix conversion technique assumes a linear relationship of the signal strengths; i.e. the energy received in any one filter is merely the sum of the energies of each of the components. This is true only when the molecules in the front of the plume are of sufficiently low density that they do not obscure molecules in the back of the plume. The exponential Beer-Lambert law applies for description of the non-linear change in emittance:

$$E_\lambda = 1-\exp(-a_\lambda x)$$

where E is the emittance

exp is any suitable logarithm base

a is the absorbtivity (equal to the emissivity under the assumptions of Kirkoff's law) scaled to the base

λ is wavelength

x is the quantity (path x density) of emitter

Therefore, the exponential character causes the proportions to change relative to those observed in the original data matrix. The effect is that a new spectrum exists for which information is lacking in the system. The system can only handle those signals which it knows exactly or an error ensues. In general the error will be small compared to the direct interference. However, it would be possible to incorporate a feedback system whereby a computed measure of ash-to-CO_2 signal is taken as a controller of the inverted matrix coefficients. Use of an exponential electrical control could then servo the coefficients and cause a tracking of the flyash effects. The SO_2 signal would then be extracted in the usual manner. While this can be readily simulated on a computer, its implementation in a system the size of the present SO_2 sensor may be difficult.

A further assumption of linearity which did not hold on practical evaluation was that of the CO_2 emissivity. It was anticipated that the CO_2 emissivity and the SO_2 emissivity would increase in similar proportion as a function of temperature. However, the very nature of the system requires that a trace constituent be referenced against a majority constituent. Thus the trace constituent is measured at a strong radiation band while the reference constituent is measured at a weak radiation band. This is necessary to effectively match the signal strengths within the computer and limit dynamic range. Unfortunately, it is characteristic of the weak bands that they are very temperature sensitive. The weak bands represent vibrational non-linearities in the radiating molecules, and may not exist at low temperature. Therefore, their existence is predicated on a temperature sensitivity.

The change in emission is not large compared to that due to the Planck radiation function of temperature. If the original spectral data is taken at a temperature in the immediate vicinity of the target plume temperature, an adequate match will pertain as in Figure 6.

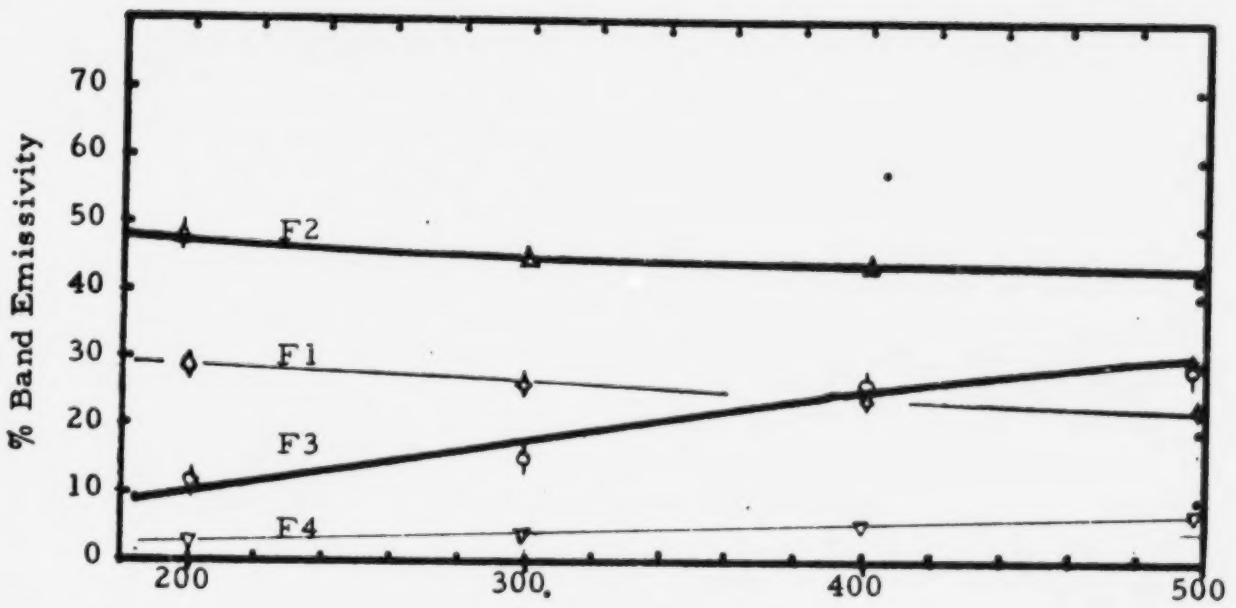


FIGURE 6. GAS EMISSIVITY

Curves of emissivity versus temperature in the bands of filters 1, 2, 3 and 4. Quantity of gas is 100 atmosphere-centimeters CO_2 plus one atmosphere-centimeter of SO_2.

A third problem remains concerning the variability of the background. The sensor presently subtracts the background by memory, i.e., the sky is viewed and a balance of the system made; the sensor is then aimed at the plume and the background signal is subtracted from an internal reference (the memory). Thus, when the background changes, the background subtraction signal will be in error. This generally is not a problem but during certain types of weather, such as low scattered cumulus conditions, the background changes more rapidly than an operator can keep up with. It is appropriate to consider the incorporation of a field of view dithering device which shifts the field of view from the plume to the background rather than from the plume to the reference as now occurs.

A Dalmo Victor funded mechanical mockup was built and tested for this concept. A general feasibility was demonstrated but the device was not incorporated in the present sensor.

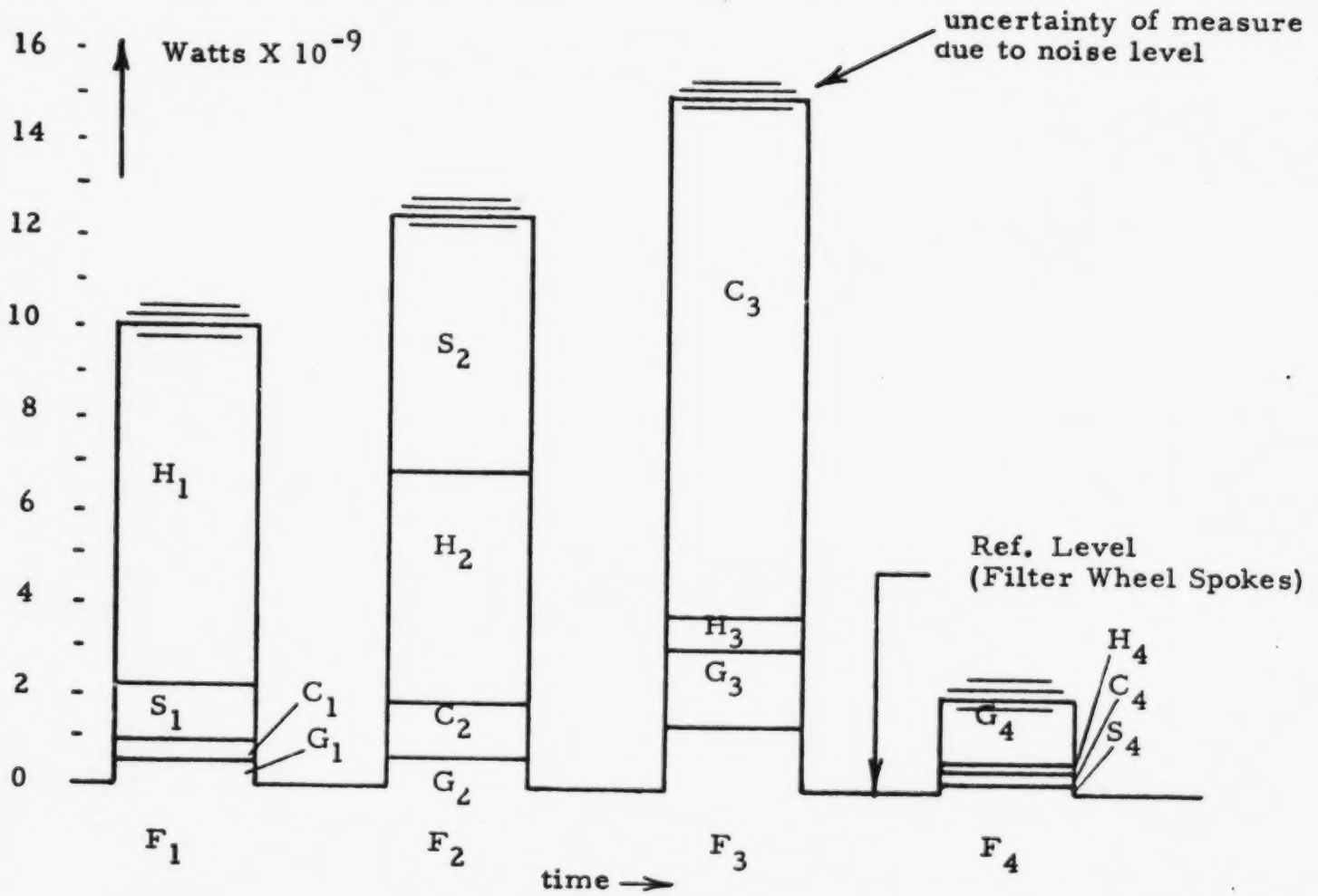
PART II

INTRODUCTION

A presentation of the SO_2 Sensor specifics follows. The majority of the sensor subsystem designs are state-of-the-art; therefore, the descriptions go into the subsystem organization, and design criteria, but not the circuit level details. A mathematical development which presents the formulae implemented in the sensor is also given.

Preliminary Discussion

The following material centers around the manipulation of the signal train shown in Figure 7. Quantitative sensors are most commonly designed around a scheme of separation of the subject material with a suitably linear transducer providing an easily amplified electrical output. As can be seen in Figure 7, the optical transducer does not separate the SO_2 radiation from its radiation environment. The transducer, consisting of an infrared bolometer, has only the benefit of the four filters of Figure 8 to separate SO_2 radiation from its environment. In turn, the radiation environment consists of emissions from those components shown in Figure 9. The phenomana of these three figures are the heart of the following development.



Where:

H_1 is $a_{11} E_1$, H_2 is $a_{12} E_1$ - - - -

S_1 is $a_{21} E_2$, S_2 is $a_{22} E_2$, . . .

etc.

Figure 7. SO_2 Sensor Signal Components

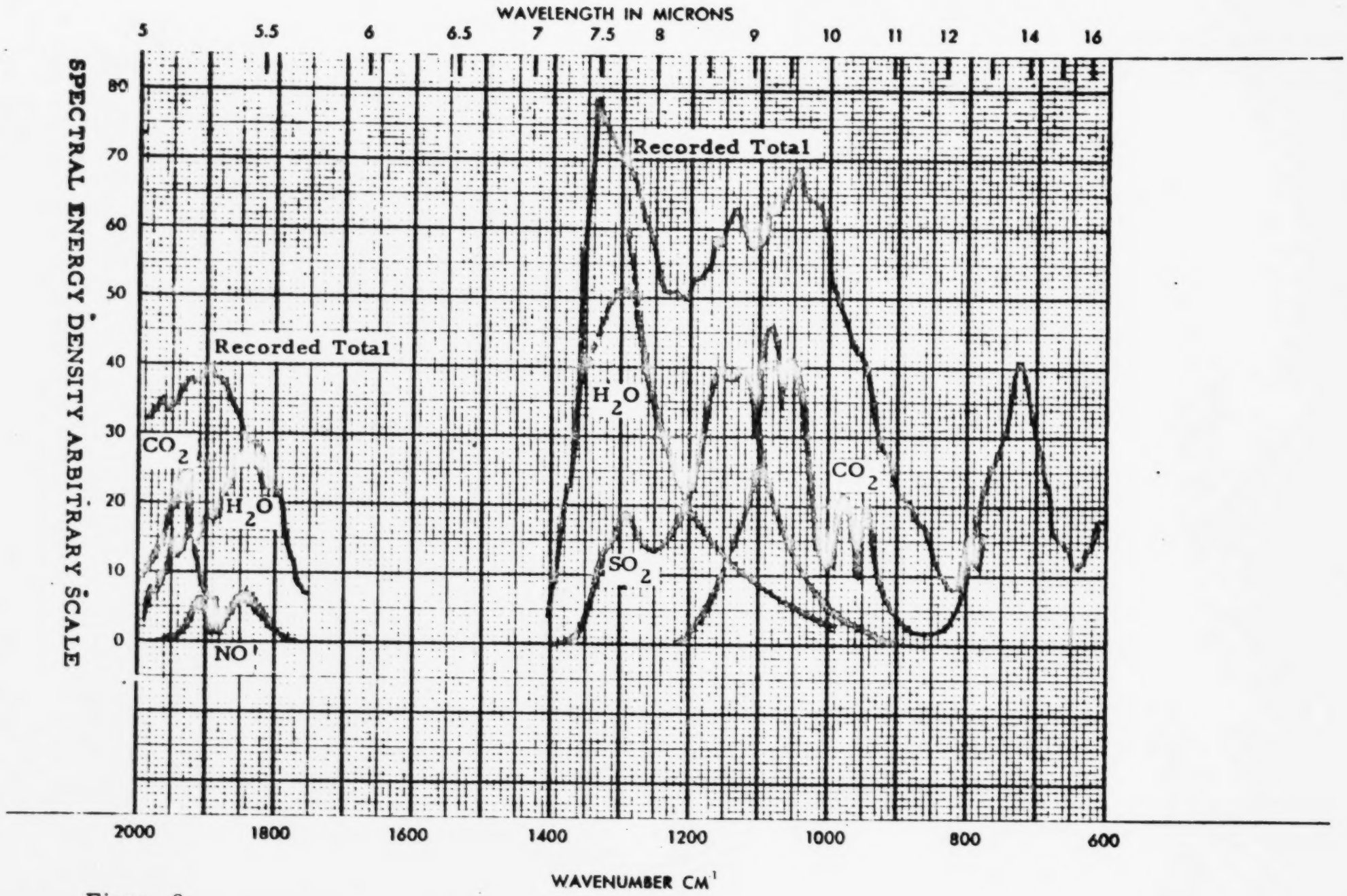


Figure 8.
Coal Burning Plume Spectrum From Moapa, Nevada (Lower Curves are for the estimated spectral contribution of the gases in the plume.)

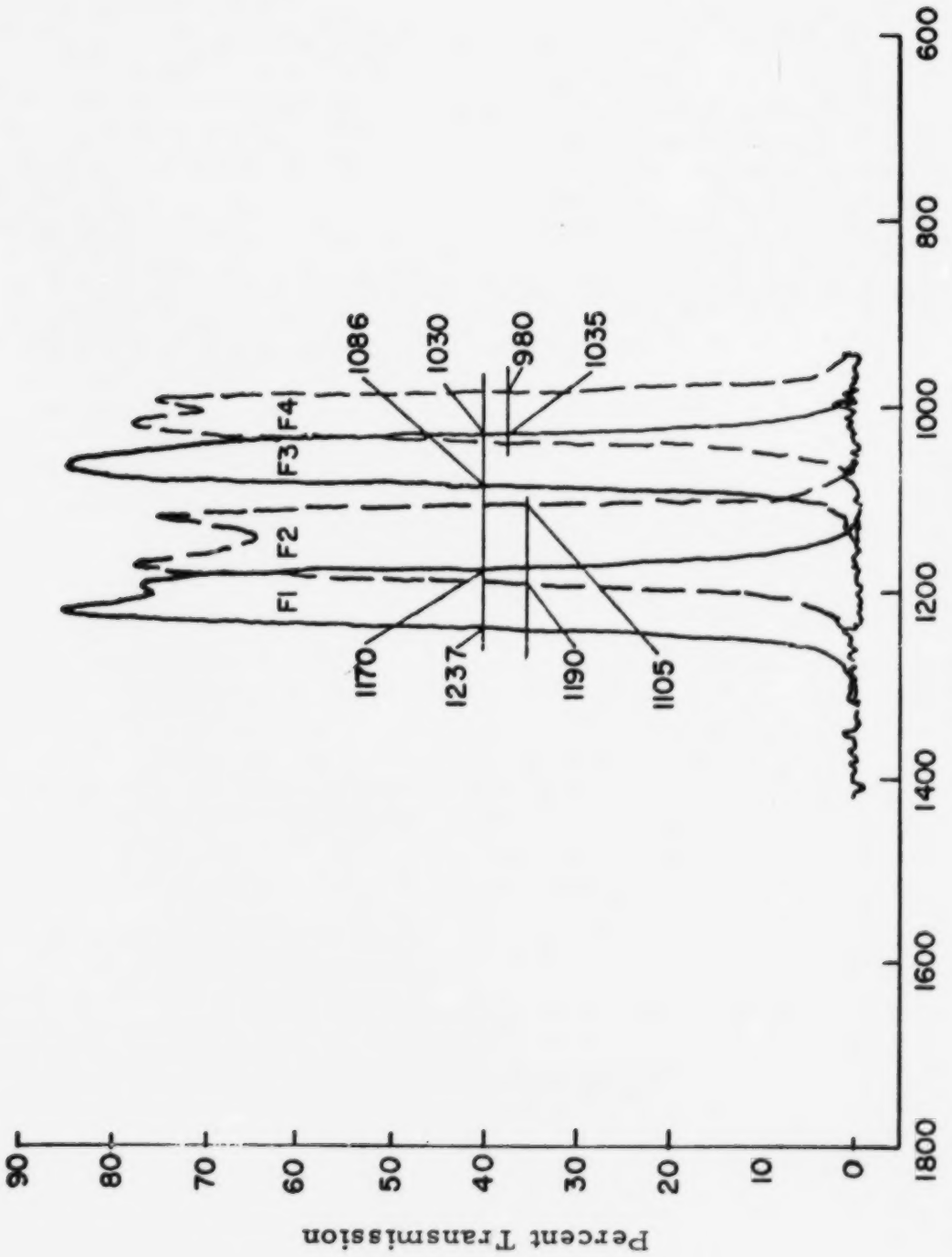


Figure 9. Filter Characteristics

PART II

TECHNICAL ASPECTS

A. SIGNAL PROCESSOR DETAILS

The signal processor is made up of four main sections: Preamplifier, Background Balance, Matrix Solution and Ratio Computation. The following is a functional description of the sections as shown in the block diagram Figure 10.

1. Preamplifier

The Infrared Detector (IR DETEC) and the preamplifier (PREAMP) are mounted in the preamplifier housing near the chopper wheel. The infrared detector, an immersed thermistor bolometer, receives the incoming radiation and converts it to an electrical signal. The preamplifier amplifies the signal so that it is large enough to be processed by the circuitry which follows. The band pass filter (BPF) reduces the range of frequencies which can be passed, thus reducing the noise level. The band pass filter is actually included as part of the preamplifier.

2. Background Balance

The balance potentiometers (BAL POT) are controlled by four knobs on the operating panel. The voltage from the balance potentiometers is gated into the main signal channel by the balance gate (BAL GATE). The balance gates are switched on during appropriate intervals which relate to the incoming radiation which requires balancing. Combining of the balance signals with the main signal is done in the balance summing network (BAL SUM). The combined signals are routed to both the automatic gain control (AGC) and the logarithmic amplifier (LOG AMP). The logarithmic amplifier output is read on the monitor meter when the function switch is in the operate position.

3. Matrix Solution

The AGC, in addition to amplifying, maintains the signal at a constant level in order to keep the required dynamic range of the computer at a minimum. The four synchronous clamps (SYNC CLAMP) are used as gates as well as clamping circuits. The synchronous clamps effectively decommutate the signal into its four components. Each synchronous clamp is gated on during the appropriate interval in order to select the appropriate pulse. The four filters convert the pulses into DC voltages which provide constant signals to the four differential amplifiers (DIFF AMP). Balancing of the four channels is

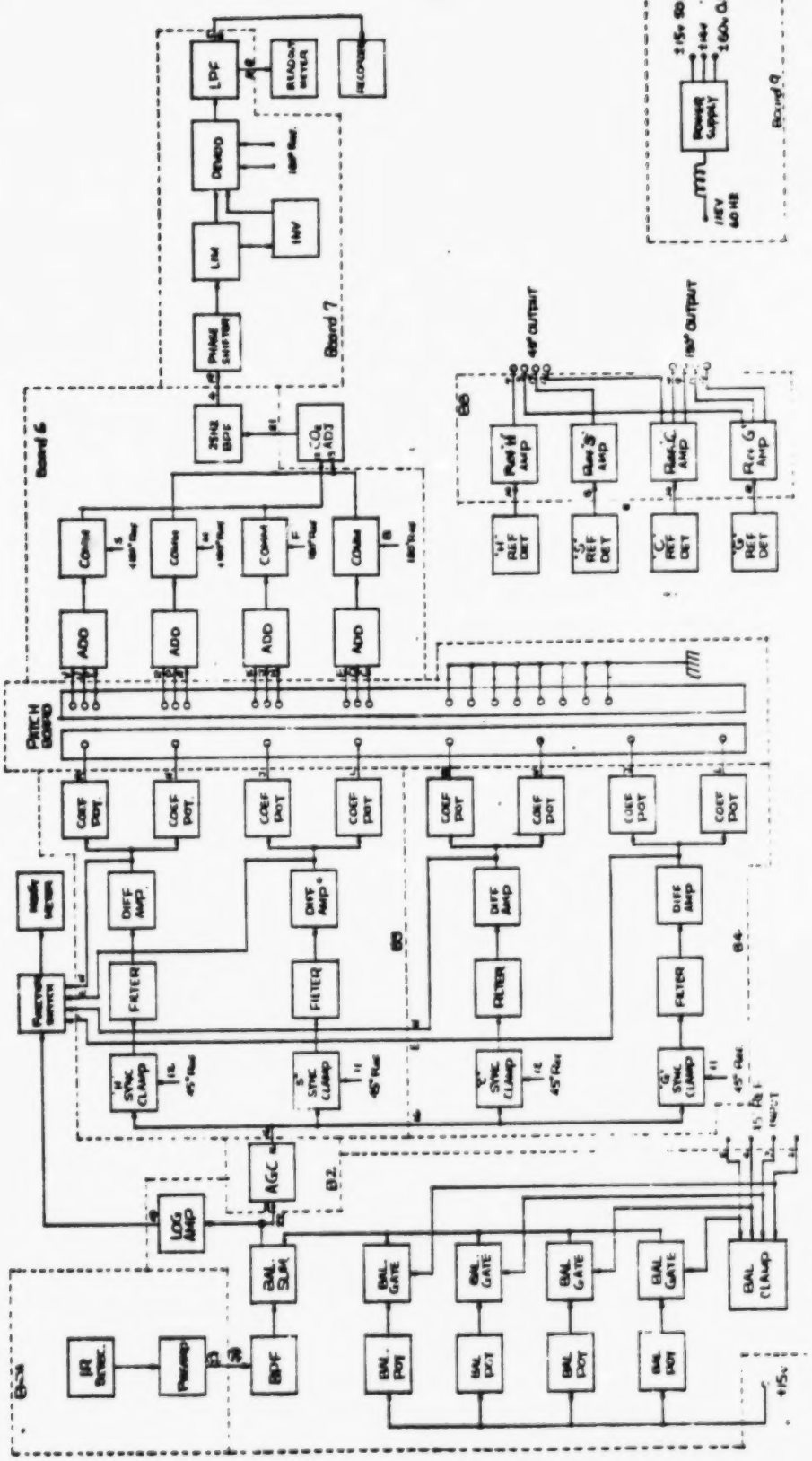


Figure 10. SO_2 Functional Block Diagram

done, while monitoring the outputs of the differential amplifiers one at a time, by using the function switch and reading the monitor meter. The output of each differential amplifier is also routed to two coefficient potentiometers (COEF POT). There are eight coefficient potentiometers which are used to adjust the eight coefficients of the matrix. The outputs of the coefficient potentiometers go to the patch board from where they are appropriately combined in the four adders. The manner in which they are combined is determined by their positions in the matrix. The outputs of the adders are four DC voltages which are then combined into one AC signal by means of the commutator. Two of the four commutator positions are tied together, forming the SO_2 analog signal. These two positions are 180° out of phase with each other; therefore, their inputs can be considered as positive and negative SO_2 analog signals. The other two commutator positions are tied together and make up the CO_2 signal. These two positions are also 180° out of phase with each other and are 90° out of phase with the SO_2 positions.

4. Ratio Computation

The CO_2 and SO_2 signals are added together in the CO_2 adjust control (CO_2 ADJ) which provides a variable degree of addition. The CO_2 adjust control is located on the operating panel. The output of the CO_2 adjust control consists of a four segment rectangular waveform. In order to read out the ratio of SO_2 to CO_2, it is necessary to extract the fundamental frequency from this waveform and compare its phase with a reference signal. The 25 Hertz bandpass filter (25 HZ BPF) extracts the fundamental frequency, which is then sent through a phase shifter and into the phase detector. The phase detector is made up of the limiter (LIM), the inverter (INV) and the demodulator (DEMOD). The output of the demodulator is a DC voltage which is proportional to the phase difference between the fundamental signal and the reference. The considerable noise in the demodulator output is reduced substantially by the averaging effect of the low pass filter (LPF), which has a time constant of 30 seconds. The long time constant prevents the readout meter from bouncing noticeably and therefore allows easy reading of the meter. The recorder reads the same as the meter and provides a permanent record of the readout as a function of time.

There are four reference detectors (REF DET) which receive optical signals from four light bulbs. The signals are synchronized with the main signal at the infrared detector. The square wave pulses from the reference detectors are amplified by four reference amplifiers (REF AMP) which put out two lengths of synchronizing pulses. Four of the outputs provide pulses which are 45° of the cycle in length. These are used for driving the synchronous clamps and the balance gates. The other two outputs provide 180° pulses which drive the commutator and the demodulator. All of the functions of the signal processing are synchronized.

The power supply provides the system with all of the DC power required for the circuits. There are six different voltages supplied. The majority of the circuits operate from the +15 and -15 volt outputs. The +14 and -14 volt outputs have a higher degree of filtering and are used in the preamplifier and AGC circuits where power supply noise could be a problem. The +60 and -60 volt outputs are highly-filtered, low-noise voltages which are used to bias the infrared detector.

B. CONSTRUCTION DETAILS

The general configuration chosen to implement the SO_2 device offered opportunities toward modularity in both manufacturing and assembly. The lower optical assembly alignment was founded on careful mounting of the chief optical parts into mechanical parts which were held with tolerances in the direction of squareness to the optical axis and perpendicularity to the chosen alignment surface.

The alignment surfaces were gibs indicated into place and parallelism. The focusable motion of the parabola allows a tolerance on position of the 45^{o} mirrors. The rotational adjustment of the 45^{o} mirrors permits adjustment in the cross instrument direction for both the position of the detector and the transfer mirror for the instrument alignment sight. Preliminary alignments of both optical paths were made at short range and final adjustments were made over an 800 foot range by maximizing the detector signal through adjustments and then alignment of the optical sight to the visible source of energy to coincide with the instrument optical path. Some parts were then pinned in place to permit disassembly.

The chopper wheel and its position reference are in the same assembly as the detector and detector preamp. As part of the optical path, the assembly is adjustable for position in the preliminary mechanical alignment. The 60 cycle motor speed is varied slightly using an O-ring drive and ratioed pulleys to avoid harmonic interference.

The upper electronic assembly is designed to be modular electronically and pre-tested. When final optical assembly is complete the position is pinned for reference.

Access doors on the final assembly together with the top cover offer sufficient access for "tuning" and general testing. The variable focus feature, of course, requires a rear door for loosening the parabolic mirror stop, focusing, and tightening the stop to prevent inadvertent sliding.

The electronic circuits were designed toward functional assembly for simple access or revision and repair. The cover acts as a retainer. The circuit design was sufficiently considered to elimate a requirement for cooling or temperature control.

C. COMPUTATION THEORY

TABLE A

SYMBOLS

A - raw data matrix

a_{ij} - member of **A**, the ratio of F_j/E_i for a single gas, other E's being zero

B - inverse of matrix **A**

C - mnemonic for CO_2 liberally applied for i = 3 or j = 3

c - scale factor incorporating proportions of SO_2 and CO_2 throughput

D - normalized version of matrix

D - denominator in ratio calculator

d_{ij} - a member of **D**, a coefficient entered in the sensor computer

E - a row vector, each component of which is a different, independent source; e.g. E_2 is SO_2 radiation only

E_i - energy due to a single source

F - a column vector, each member of which is the sum of fractions of all four sources of radiation

F_j - signal received through the jth filter, a member of **F**

G - mnemonic for ash (grey-body) liberally applied for i = 4 or j = 4

H - mnemonic for water (H_2O) liberally applied for i = 1 or j = 1

i - row index where i = 1 denotes H_2O radiation
= 2 denotes SO_2
= 3 denotes CO_2
= 4 denotes ash

j - column index where j = 1 denotes radiation in the 8.3 micron band
= 2 denotes radiation in the 8.7 micron band
= 3 denotes radiation in the 9.4 micron band
= 4 denotes radiation in the 9.9 micron band

N - numerator in ratio calculator

S - mnemonic for sulfur dioxide (SO_2) liberally applied for i = 2 or j = 2

C. COMPUTATION THEORY

Each of four plume components is radiating energy E_i. (Refer to Table A for definition of symbols).

We wish to measure the source concentration (% SO_2), and the energy E_2 is taken as the measure of that concentration. Through each filter of the sensor a signal F_j is received from energy Source E_i. Since each spectrum overlaps the other, more or less, the signal F_j receives not only energy E_i, but proportions a_{ij} of the other three signals as well; thus

$$F_1 = a_{11}E_1 + a_{12}E_2 + a_{13}E_3 + a_{14}E_4$$

$$F_2 = a_{21}E_1 + a_{22}E_2 + a_{23}E_3 + a_{24}E_4$$

etc.

The problem is then to separate the four unknowns, E_i using the four given signals F_j.

A concise solution is presented using matrix notation; the problem is stated:

$$\mathbf{F} = \mathbf{A} \cdot \mathbf{E}$$

where $\mathbf{F}$ is a column vector, $\mathbf{A}$ the data matrix, and $\mathbf{E}$ is the column vector with orthogonal (independent) elements.

Solving for the vector $\mathbf{E}$, we write

$\mathbf{E} = \mathbf{A}^{-1} \cdot \mathbf{F}$, where the exponent -1 indicates matrix inversion.

Details of the inversion process are unnecessary since a four by four matrix or larger is best inverted on a computer by calling up an inversion subroutine.

The new matrix $\mathbf{A}^{-1} = \mathbf{B}$ is scaled to the system electronics by an appropriate factor c (% CO_2 control) giving the largest coefficient of the system a maximum of 1:

$$\mathbf{D} = c \cdot \mathbf{B}$$

Thus the SO_2 signal is

$$E_2 = d_{21}F_1 + d_{22}F_2 + d_{23}F_3 + d_{24}F_4$$

The final form to be computed, using the mnemonics $S = E_2$ and $C = E_3$, is

$$S/C = \frac{d_{21}F_1 + d_{22}F_2 + d_{23}F_3 + d_{24}F_4}{d_{31}F_1 + d_{32}F_2 + d_{33}F_3 + d_{34}F_4}$$

Implementation of the above equation then requires that each decommutated signal, F_j, be multiplied by one d_{ij} and that the products be summed.

To obtain the data matrix **A** for generation of the sensor coefficients, d_{2j}, and d_{3j}, a set of four experiments is performed. Each consists of measurement of the four F_j with a single E_i target. Thus, a single gas or ash sample is placed in a test tank with IR windows. The tank is heated to 400 - 500°K and the signal in each of the four channels is measured. Then, from the following table **A** is extracted.

H experiment: $a_{11} = F_1/E_1 \equiv 1$ $a_{12} = F_2/F_1$ $a_{13} = F_3/F_1$ $a_{14} = F_4/F_1$

S experiment: $a_{21} = F_1/F_2$ $a_{22} = F_2/E_2 \equiv 1$ $a_{23} = F_3/F_2$ $a_{24} = F_4/F_2$

C experiment: $a_{31} = F_1/F_3$ $a_{32} = F_2/F_3$ $a_{33} = F_3/E_3 \equiv 1$ $a_{34} = F_4/F_3$

G experiment: $a_{41} = F_1/F_4$ $a_{42} = F_2/F_4$ $a_{43} = F_3/F_4$ $a_{44} = F_4/E_4 \equiv 1$

The scale is then set by running the instrument with a source of 1:100 SO_2:CO_2 and turning control %C until the sensor meter reads 0.1% SO_2 (for a nominal 10% CO_2).

The final step in the implementation of

$$S/C = \frac{\Sigma\ d_{2j}F_j}{\Sigma\ d_{3j}F_j}$$

is the generation of the ratio of the sums.

A ratio, N/D, may be taken by use of an electrical vector analog. Two phasors (vectors orthogonal by virtue of phase relationship) when summed algebraically result in a single sinusoid with its phase, θ, given by

$$\theta = \arctan \frac{N}{D}$$

The implementation of the ratio function takes advantage of the decommutation signals generated in phase with the four F_j.

At zero degrees phase the numerator components of the calculation are gated into a narrow band filter. At 90 degrees phase, the denominator components are gated into the same filter. The narrow band filter rejects harmonics above the fundamental processing frequency (25 Hz) and sums the two fundamental pulse components.

The sums of $d_{ij}F_j$ are combined at the N gate and D gate with resistors as with operational amplifiers.

Since two or three of the d_{2j} and d_{3j} will be negative while all of the F_j are positive, the negative components are gated 180 degrees later; i.e., at 180 and 270 degrees for N and D respectively. The actual circuit maximizes the signal by gating each component on for 180 degrees; thus the N gate (zero degrees phase) is on from -90 to +90 degrees.

A computer program was prepared to calculate the optimum filter spectral bandwidths and centers. The program starts with an initial estimate of the filters, and calculates the signal-to-noise ratio. It then varies each of the filters in bandwidth and center wavelength one computational increment The variation which results in the largest increase in signal-to-noise ratio is plotted, and that particular variation is continued incrementally until the improvement is less than that computed for one of the other eight variations of bandwidth and center. Thus the program is a "hill-climbing" optimization, where the direction of travel is in the direction of coordinate of steepest ascent, and the summit represents the maximum signal-to-noise ratio. Since the problem is eight dimensional, and the spectra have multiple peaks, the maximum found may be a local maximum, with a possibility of an adjacent "hill" being higher. Consistent results using several different initial conditions should eliminate the chance of a significant error in "hill" choice.

The signal to-noise-ratio is calculated with the formulae given above with the addition of noise components, $\pm u$. The noise components are generated in the bolometer and preamp and are associated with each of the filter signals in the same proportions. Since the noise components are uncorrelated, they are summed in an rms fashion as below:

$$\frac{S + f_1(u)}{C + f_2(u)} = \frac{d_{21}(F_1 \pm u_1) + d_{22}(F_2 \pm u_2) + d_{23}(F_3 \pm u_3) + d_{24}(F_4 \pm u_4)}{d_{31}(F_1 \pm u_1) + \quad . \quad . \quad . \quad .}$$

$$S/C = \frac{d_{21}F_1 + d_{22}F_2 + d_{23}F_3 + d_{24}F_4 \pm u\sqrt{d_{21}^2 + d_{22}^2 + d_{23}^2 + d_{24}^2}}{\quad . \quad . \quad . \quad . \quad \pm u\sqrt{d_{31}^2 + d_{32}^2 + d_{33}^2 + d_{34}^2}}$$

where f (u) is the uncertainty due to noise and u_n is the noise uncertainty in each channel. While the various u_n are uncorrelated, their averages are identical.

For the computer simulation it is as easy to work with the value of S or C directly. The figure of merit to be optimized by the computer is then:

$$\text{Figure of merit } Q = \frac{S}{\sqrt{\Sigma\, d_{2j}^2}} \cdot \frac{C}{\sqrt{\Sigma\, d_{3j}^2}}$$

By taking the logs of an optimization equation, a sum, rather than the product above, is seen to be the best measure; however, for the two components nearly equal, as in this case, the results are virtually identical.

The FORTRAN program and its description are available for other filter optimization projects should further applications be desired.

PART III

OPERATING INSTRUCTIONS FOR REMOTE SO_2 SENSOR

A. INTRODUCTION

Operation of the Dalmo Victor SO_2 sensor is simple and rapid. The environment is dominant with this type instrument, hence, its interpretation is critical to the operation. It is therefore seen that operation of the instrument requires only a short study while choice of operating conditions requires a degree of experience and understanding of the preceeding material - thus the "operation manual" is bound with the more detailed final report.

The first portion describes the setting of factory adjustments and nominal values chosen for the initial field trials. Description of the operation and function of the control panel, accessories, set-ups, and computation program follow.

B. GENERAL DESCRIPTION OF THE INSTRUMENT

1. Configuration as Shipped

Focus - The focus of the IR system is adjustable from infinity down to a few feet. Because of the long focal length, 12", the lack of depth-of-field is significant at ranges under a few hundred feet. The system was shipped with the focus at approximately 500 feet. A check against this value should be made with a small IR source such as a soldering iron. At 500 feet range, the blur circle is 6" in diameter +6" due to the system aperture. Focus adjustment is made by opening the rear door and loosening the two brass thumb screws over the optic rails.

% CO_2 - This control is set at 5.00 and scales the system for a 10% CO_2 concentration. With this setting, the ratio of SO_2 to CO_2 may be read directly from the % SO_2 meter with a factor of 10 multiplication. Thus a reading on the meter of 0.3 represents a SO_2 to CO_2 ratio of 3%.

2. Background Balance

An internal toggle switch is available to reverse the polarity of the background balancing signals. The switch is set in such a position that only cold backgrounds may be compensated for. Backgrounds that are warmer than the filter wheel (which is always a few degrees above ambient) may be compensated by changing the switch position to "Hot." Need of this switch is not anticipated since real targets are nearly always above the observer and consequently, provide a relatively cool background by virtue of the natural adiabatic lapse rate.

3. AGC

An internal toggle switch may be used to disable the automatic gain control capability. The AGC is presently enabled and is disabled only for certain absolute signal strength measurements.

4. Calculation Format

The patch panel of the analog computer is presently programmed to compute the ratio of the SO_2 signal to the CO_2 signal with a four vector orthogonalization. While an experienced technician may rapidly change the programming and incorporate new matrix coefficients, it is expected that the machine will be returned to Dalmo Victor should a computational format revision be required.

5. Meter Offsets

Both panel meters have a fixed mechanical offset. The percent SO_2 meter offset is on the order of 1^{o} and eliminates a slight non-linearity near zero. The signal strength meter normally sits at a reading of 10 since both the balance and signal strength can go negative. When balancing is being accomplished, the high gain of the balance readout will frequently result in off scale readings until balance is closely approached.

C. CONTROL PANEL DESCRIPTION

The primary readout of this system appears on the percent SO_2 meter. The scale of this meter is non-linear and accomplishes the analog conversion of an arctangent function to a simple ratio function. When an external recorder is used the scale must be multiplied by an arctangent function of 0 to 90^{o} with the value of arctangent 45^{o}, 1 interpreted on the scale as .1. The time constant of the SO_2 meter readout is approximately 30 seconds. For a step input in SO_2 proportion, a delay of four time constants (2 minutes) is necessary before the meter indicates 98% of the change.

Since the SO_2 meter is reading a ratio, absence of signal results in a computation of 0 over 0, which is indeterminant. Therefore, the system noise level will control the meter position and the readout will vary randomly, and include negative values.

1. Signal Strength Meter

In the operating configuration the signal strength meter reads out a log scale of the signal strength relative to the balance point. Since the signal strength meter has a short time constant to facilitate alignment and trouble-

shooting, its signal-to-noise ratio is lower than that of the ratio processor. Thus, barely discernible signal strength indications are generally enough to present a stable ratio output. In field use, the signal strength meter provides a good monitor of background disturbances and operational changes by the stack operators.

2. Boresight

The aiming telescope has a line of sight which is concentric with that of the IR system by virtue of the back-to-back diagonal mirrors. Thus parallax is eliminated. The boresight telescope is the type normally used as a pistol sight and consequently has a large eye relief; i.e. you may sight on the target with your eye removed at least 18" from the instrument's panel. This allows a peripheral vision monitoring of the signal strength meter. The field-of-view of the boresight telescope is about 2.5^{0}, while the field-of-view of the IR telescope is only 3.4 minutes. Thus, accurate centering with cross hairs on the target is desirable.

3. Balance Control

Since there is a radiative exchange of energy at this sensor's wavelength between it and virtually everything in the field-of-view, a balance against the background is necessary. The balance controls introduce synchronous electric signals ahead of the AGC and are electrically equivalent to signals generated in the field-of-view. When the system is set up for compensation of cold background, the sign of the electrical balance signal is identical with that of a hot gas in the field-of-view. Thus the balance controls may be used to introduce simulated signals in any proportion.

Balance controls are independent, and operate continuously. To balance the H channel, turn the function control from Operate to H. The signal strength meter will read only the H channel. The meter scale is expanded about zero, and serves as an error detector. Balance occurs at a reading of 10 microamps.

For typical operation the balance controls will be operated at about 10% of their full scale capability. Note that with the present computational matrix adjustment of the fourth channel balance (gray) is extremely important. Large proportions of the signal generated in the fourth channel are subtracted from the other three channels because of the broad spectrum nature of flue gas aerosols.

4. Percent CO_2 Control

To transform the SO_2 to CO_2 ratio to a percent of combustion products, the fraction of CO_2 for the target fuel must be entered in the computation. Since it was indicated that the simple SO_2 to CO_2 ratio is the desired measure, a conversion scale of control setting to percent CO_2 has not been provided, but rather the value has been fixed for a 10% ratio. This gives, as noted above, a center scale reading of 1:100 for SO_2 to CO_2.

5. Recorder Output

The recorder output is by a standard BNC connector with a current source at full scale of 100 microamps. The current readout may be readily changed to other formats if required by your instrumentation.

6. Preamp Output

The preamp output is provided as a quick look debugging aid for monitoring the unprocessed signal. The unprocessed signal wave shape is dominated by a signal due to the temperature difference of the filter wheel and the background. Since the target is normally 90% transparent, it does not show up significantly in the unprocessed signal. Because of the low level nature of the preamp signal, care must be used to prevent coupling interference into the system through unshielded or improperly grounded leads.

D. ACCESSORIES

Tripod Rigidity - While the tripod seems substantial enough, particularly if hand carried a distance, precise alignment requires mounting on a very rigid table. In the field a certain amount of sheltering for wind gusts is recommended if the target dimensions are small compared to the field-of-view (1 milliradian).

1. Azimuth Scan

The slow azimuth scan drive is provided with an elementary mechanical engagement. The drive motor is a synchronous clock mechanism with a very small output shaft diameter. Forced rotation of the panhead without disengagement of the clock gears will break the shaft. The clock motor is not reversible, thus at the end of a scan the gears must be manually disengaged and the panhead control crank used to reposition the field-of-view.

2. Recorder

While the recorder we have shipped with the sensor has proven to be well worth the less-than-$200 cost, it generates interference under certain power line impedance conditions. When the sensor system is used with this recorder a check for interference should be made. The interference is generated by the servo motor of the recorder and conducted into the sensor system through the AC power lines. Several attempts to remedy this by both the manufacturer and our laboratory have been unsuccessful.

E. LAB SET-UP

A demonstration of the system operation may be made with internally generated signals. With the door closed, the field-of-view remains constant, then artificial signals may be introduced and superimposed from the data matrix below via the balance controls. The data matrix columns list by filter the proportion of signal for each channel into a single plume constituent, normalized to the dominant filter. The coefficients which are presently entered in the sensor computer are extracted from the inverted matrix following the data matrix.

Relative Signal Strength Matrix

	H_2O	SO_2	CO_2	ASH
H Signal	1	0.52	0	0.534
S Signal	.49	1.00	0.1	0.988
C Signal	.21	0.10	1.0	1.0
G Signal	.19	0.04	0.63	0.811

Inverted Matrix

	F_1 (or H)	F_2	F_3	F_4
H_2O	1.36861	-.729524	.361925	-.458686
SO_2	-.230724	1.02973	2.65092	-4.37126
CO_2	.201275	-.313185	3.91809	-4.58217
ASH	-.465611	.363411	-3.25918	5.11562

Values from the inverted matrix give a direct measure of the sensitivity of each channel. By entering the values for a CO_2 signal only, the percent SO_2 meter will read approximately zero. Note that exact computation requires measurement of internal voltages due to signal loading on the balance potentiometers. A CO_2 signal might be entered as follows:

H Knob	0.000
S Knob	0.010
C Knob	0.100
G Knob	0.063

Adding SO_2 to the CO_2 signal will result in a center scale reading with 1 to 1 proportions as follows:

H Knob	0.052
S Knob	0.110
C Knob	0.110
G Knob	0.067

Entry of SO_2 data only, e.g.

H Knob	0.052
S Knob	0.100
C Knob	0.010
G Knob	0.004

will result in a reading of approximately 100%. Entry of values for H_2O or ash alone will result in indeterminant output while addition of those components with CO_2 or SO_2 signals should cause no change in output. Note again that these values are approximate when entered in an open loop fashion via the balance control scales.

F. FIELD SET-UP

Inspection of the field-of-view and background must show clear, unchanging regions which may be used for the target and reference. After setting up the instrument, and allowing a few minutes for thermal balance within the optical system, aim the sensor a few degrees (about one telescope FOV) upwind of the target and balance each of the four channel positions and bring the signal strength reading to a nominal value of 10. Since the system will be seeing no signal as it balances, the automatic gain control will be working wide open, causing the individual channel signal strength to appear noisy. Thus it is necessary for the operator to balance the signal level at an

average reading of 10 using several seconds of monitoring to ascertain an average value. As noted above, the G-control is particularly sensitive. Return the function control to Operate and the signal strength meter should now indicate no signal. A few minutes monitoring of the recorded percent SO_2, giving completely random output will assure the operator of a balanced condition. After balancing, slew the azimuth until the cross hairs of the telescope are within the cone of undisturbed flow at the stack top. This cone of undisturbed flow will become obvious to the operator after some field observation. The undisturbed flow cone typically runs from the edge of the stack to a height of 1/2 to 1-1/2 stack diameters. For very clear burning stacks, a good estimate of the wind direction from other sources will enable the operator to estimate the optimum field-of-view. When the sensor is viewing a target plume, monitor the signal strength meter and the battery power supply output to correlate transients and drifts when the record is reviewed later. Two minutes after the last disturbance, e.g. azimuth slewing, the panel meter should be read. The most accurate estimate of a particular target SO_2 strength should be recorded in about 10 time constants (10 x 30 sec = 5 minutes). At the end of the monitoring period, or every 20 to 30 minutes, the sensor should be slewed in azimuth to the reference background and checked for balance. Background spectra due to pollution or diurnal changes in high altitude ozone background can occur without any visible evidence. If the background consists of uniform low level clouds, balance check should be made every few minutes. This is because the cloud-bottom altitude may change rapidly. At the end of the target run several minutes of reference view is advisable to be sure that the output is random.

G. MATRIX COEFFICIENTS, CALIBRATION AND PROGRAMMING

The purpose of this section is to provide the operator with the information required to calibrate and program the DV SO_2 sensor.

The relative signal strength matrix will be used with the balance pots to perform an internal electronic check on the operation of the instrument. The inverted matrix will provide the values for the coefficient pots. The technique of obtaining the coefficient values is as follows:

From the inverted matrix select the two rows of four columns that represent the type of measurement that is to be performed. For example, to measure the ratio of SO_2/CO_2 we would select the following rows and columns of the B matrix; an example is presented below:

	H	S	C	G
H_2O	1.3681	-.729524	.361925	-.45868
SO_2	-.230724	1.02973	2.65092	-4.37126
CO_2	.201275	-3.3185	3.91809	-4.58217
ASH	-.465611	.363411	-3.25918	5.11562

These values are now normalized to the largest number, -4.58217, taking rows of the D matrix:

SO_2	-.05035	+.2247	+.5785	-.9539
CO_2	+.04392	-.0724	+.8851	-1.0

As marked on the instrument, the top row now will have the subscript of S, the bottom row C. Therefore the data may be written as follows:

Hs	-.05035	d_{21}
Hc	+.04393	d_{31}
Ss	+.2247	d_{22}
Sc	-.07242	d_{32}
Cs	+.5785	d_{23}
Cc	+.8551	d_{33}
Gs	-.9539	d_{24}
Gc	-1.0	d_{34}

To adjust the coefficient pots, proceed as follows:

Remove all patch plugs from the patch panel. While adjusting the coefficient pots, patch in only one calibrate voltage at a time.

Patch	Measure	Adjust	For VDC
A_1-A_2	C_1-E_{10}	H_s	.05035
A_1-A_2	C_2-E_{10}	H_c	.04392
A_3-A_4	C_3-E_{10}	S_s	.2247
A_3-A_3	C_4-E_{10}	S_c	.07242
A_5-A_6	C_5-E_{10}	C_s	.5785
A_5-A_6	C_6-E_{10}	C_c	.8551
A_7-A_8	C_7-E_{10}	G_s	.9539
A_7-A_8	C_8-E_{10}	G_c	1.000

Patch the Differential Amp outputs to their respective coefficient pots.

A_1-B_1
A_3-B_3
A_5-B_5
A_7-B_7

In the event you are working a two vector or a three vector problem, leave out the appropriate jumper at this point.

To determine which coefficient pots go to which commutator inputs proceed as follows:

Patch between rows C & D connecting the subscripts S of the C row with the S inputs of the D row. Care should be taken with respect to any negative signs. For example, Hs was found to be -.230724. Therefore, Hs will be connected to a -S input, i.e., C_1-D_1. The same procedure will be followed with the C subscripts, patching them with the C input on row D.

H. TEST

With the aperture closed, balance all four channels and add the relative signal strength matrix values to each of the balance pots. In this case for CO_2 add:

H	0.00
S	.010
C	.100
G	.063

The percent SO_2 meter will read approximately zero. By using the SO_2 values the meter will read full scale.

H	.052
S	.10
C	.01
G	.004

I. PATCH PANEL CONFIGURATION

A1		H channel coefficient input
2		Calibration voltage
3		S channel coefficient input
4		Calibration voltage
5		C channel coefficient input
6		Calibration voltage
7		G channel coefficient input
8		Calibration voltage
9		-
10		-
B1		H channel Diff-Amp output (F_1)
2		
3		S channel Diff-Amp output (F_2)
4		-
5		C channel Diff-Amp output (F_3)
6		-
7		G channel Diff-Amp output (F_4)
8		-
9		-
10		-
C1	H_s	Coefficient output
2	H_c	"
3	S_s	"
4	S_c	"
5	C_s	"
6	C_c	"
7	G_s	"
8	G_c	"
9	-	"
10	-	"
D1	-S	Commutator input
2	C	"
3	S	"
4	-C	"
5	S	"
6	C	"
7	-S	"
8	-C	"
9	-	"
10	-	"

E1	Pre-Amp output
2	AGC input
3	AGC output
4	-
5	Bandpass filter output
6	180° reference
7	90° reference
8	+15 VDC
9	-15 VDC
10	Common

This completes the calibration and electronic checkout. The instrument is now ready for use.

To solve other types of problems, for example, a measurement of H_2O/CO_2, the same technique is used with the inverted matrix; in the case of H_2O/CO_2 we would use the data from the first and third rows and proceed as we did with the second and third rows for SO_2/CO_2.

When the sensor is ready for the field, the following figures will be helpful in determining target suitability. Figure 11 gives curves of constant received energy as a function of stack temperature and diameter. The curve showing typical sources is estimated from data in "Atmospheric Emissions from Coal Combustion - An Inventory guide", PHS, Cincinnati, Ohio, 1966. Since temperature will generally not be directly measured, the curves can only serve as a guide.

Figure 12 shows the range for two limits of water vapor which obscurs radiation at the 8 micron edge of filter 1. Such observation indirectly effects the SO_2 reading by causing a low reading of the F_1 signal. The sensor, in effect, uses F_1 as a measure of how much water vapor signal to subtract from the signal in F_2, the SO_2 primary measure. If water vapor in the stack plume is low to begin with, errors will be less than a few percent even for the 5 mm H_2O scale values. If high accuracy is required and/or the fuel is rich in hydrocarbons, the scale should be slid to the 1 mm H_2O range. F_1 will be in error by about 1-2% for every millimeter of water in the radiation path. Since H_2O signal in F_2 is half that in F_1, the percent error is halved in the computation.

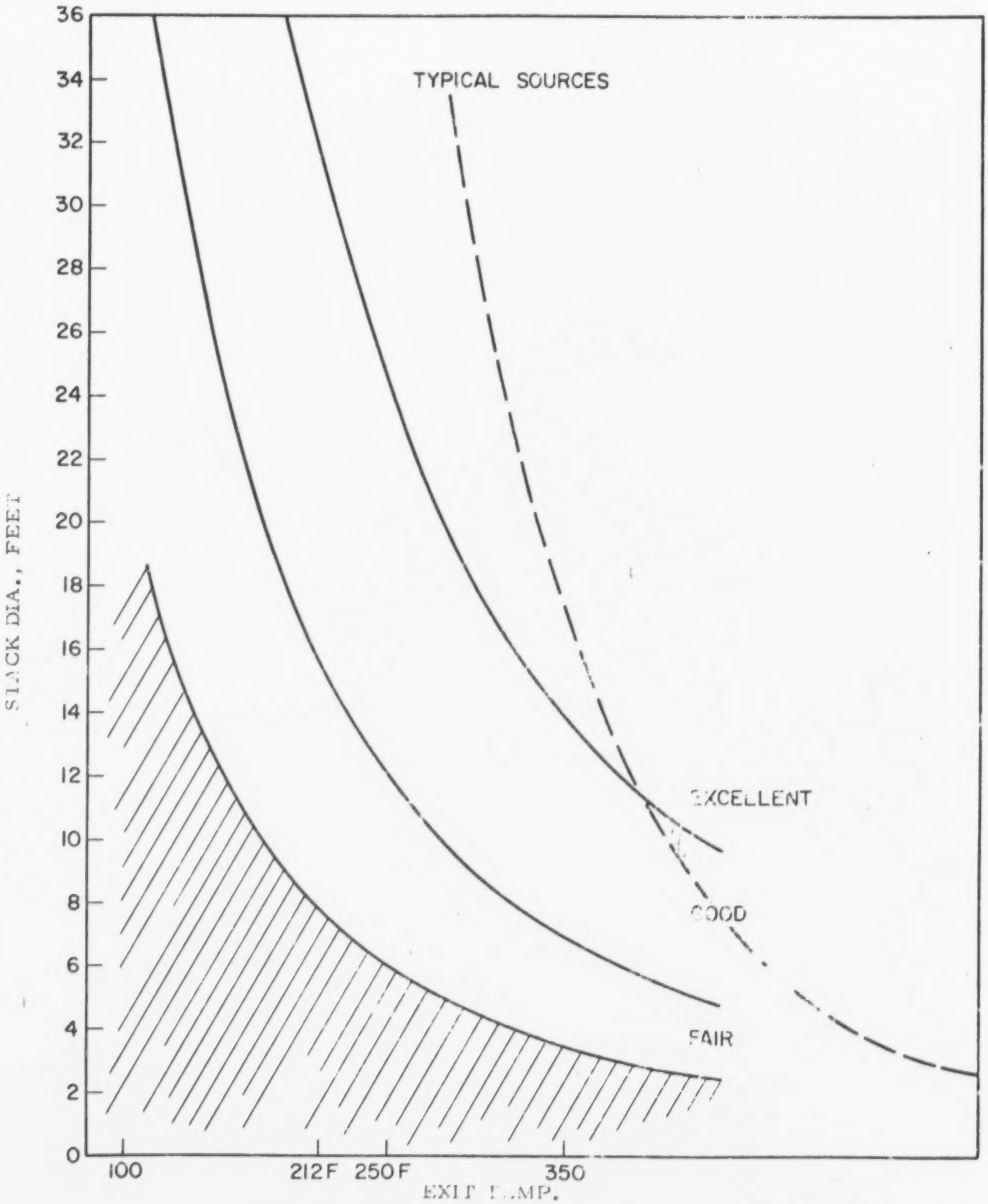


Figure 11. Typical SO_2 Sensor Operatio..

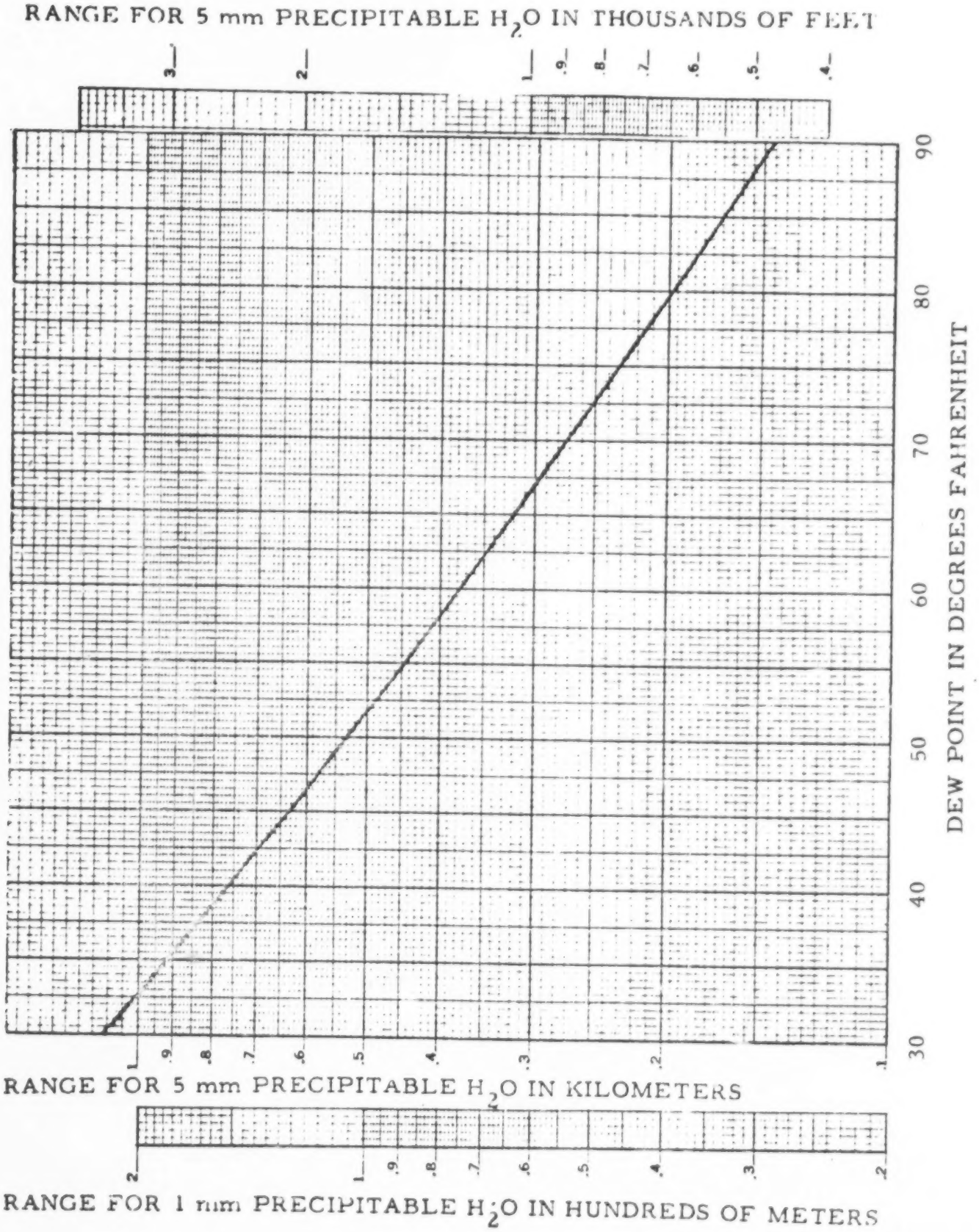


FIGURE 12.

RANGE DUE TO ATMOSPHERIC WATER VAPOR